NUMERICAL ANALYSIS ON SIMPLIFIED 2D MODEL OF HEART VALVE LEAFLETS DURING CARDIAC CYCLE

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ABSTRACT

Nowadays, the increasing numbers of heart diseases cases is very worrying although the medication technologies are always improving and moving forward. In this study, the objectives are to investigate the effect of blood flow velocity and leaflet displacement by using different shape of simplified two dimensional heart valve leaflets in the diastolic and systolic condition. Five different shapes of mitral valve leaflets and aortic valve leaflets were created and the simulation was performed by using ADINA-Fluid Structure Interaction. From the result obtained, triangle shape of leaflet showed it had the highest of blood velocity changes and leaflets displacement changes in a period time of one second when compare to the other four shapes whereas the square shape had the lowest performances. The relationship obtained for blood velocity flow and leaflet's displacement changes is same for both mitral valve and aortic valve. The velocity of flow and leaflet's displacement changes for triangle shape in diastolic condition is 68.54 mm/s and 2.171 mm while at systolic condition is 102 mm/s and 5.168 mm respectively for mitral valve. The outcome simulation result shows that large vortex formed behind the leaflet and leaflet deformed when the blood flow into left ventricle is agreed with the result in literature. In conclusion, five different shapes two-dimensional model of mitral valve and aortic valve has been developed and ellipse shape of valve leaflets is predicted to be the most suitable shape in applying for future artificial valve designing due to its good blood velocity flow with the small changes of leaflets displacement. Ellipse shape of leaflets could be chosen as the most suitable shape among these five shapes in further study of heart valve simulation.

ABSTRAK

Pada masa kini, nombor meningkat penyakit jantung kes amat membimbangkan walaupun teknologi ubat sentiasa memperbaiki dan bergerak ke hadapan. Dalam kajian ini, objektifnya adalah untuk mengkaji kesan halaju aliran darah dan anjakan risalah dengan menggunakan bentuk yang berlainan dipermudahkan dua dimensi risalah injap jantung dalam keadaan diastolik dan sistolik. Lima bentuk yang berlainan risalah risalah injap mitral dan injap aorta telah diwujudkan dan simulasi telah dijalankan dengan menggunakan Interaksi Struktur Adina-Bendalir. Berdasarkan keputusan yang diperolehi, bentuk segitiga risalah menunjukkan ia mempunyai perubahan halaju darah dan perubahan anjakan risalah yang tertinggi dalam masa tempoh satu saat apabila berbanding dengan empat bentuk yang lain manakala bentuk persegi mempunyai prestasi terendah. Hubungan yang diperolehi bagi halaju aliran darah dan perubahan anjakan risalah adalah sama bagi kedua-dua injap mitral dan injap aorta. Halaju aliran dan perubahan anjakan risalah untuk bentuk segitiga dalam keadaan diastolik adalah 68,54 mm / s dan 2,171 mm manakala pada keadaan sistolik adalah 102 mm / s dan 5,168 mm masing-masing bagi injap mitral. Keputusan hasil simulasi menunjukkan bahawa pusaran besar dibentuk di belakang risalah dan risalah yang cacat apabila aliran darah ke dalam ventrikel kiri bersetuju dengan keputusan dalam kesusasteraan. Dalam Kesimpulannya, lima bentuk yang berlainan model dua dimensi injap mitral dan injap aorta telah dibangunkan dan bentuk elips risalah injap yang diramal menjadi bentuk yang paling sesuai dalam memohon untuk masa depan injap tiruan merekabentuk kerana halaju aliran darah yang baik dengan kecil perubahan anjakan risalah. Bentuk elips risalah boleh dipilih sebagai bentuk yang paling sesuai di kalangan kelima-lima bentuk dalam kajian lanjut simulasi injap jantung.

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LIST OF SYMBOLS

A	Cross sectional area
P	Pressure
E	Young's modulus elasticity
a	Acceleration
σ	Stress
ε	Strain
m	Mass
V	Velocity
t	Time
$\dot{m}$	Mass flow rate
F	Force
Ma	Mach number
Cp	Specific heat
T	Temperature
v	Kinematic viscosity
μ	Viscosity
ρ	Density
%	Percentage

LIST OF ABBREVIATIONS

ADINA	Automatic Dynamic Incremental Nonlinear Analysis
FSI	Fluid Structure Interaction
2D	2 dimensional
UMP	University Malaysia Pahang
ALE	Arbitrary Lagrange Euler
FEA	Finite Element Analysis
MRI	Magnetic Resonance Imaging

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

This chapter will describe about the background, problem statement, objectives and scope of the study. From the background of the study, it comes out the problem statement and from the problem statement; the purpose of this study can be identified. This study will be based on the objective that have been determined and is limited by the scopes.

1.2 BACKGROUND

The human heart is a double pump enabling the pulmonary and systemic circulation of blood. It is divided into four chambers which are the right atrium, right ventricle, left atrium and left ventricle. The left and right atrium and the left and right ventricles are separated from each other by a wall of muscle called the septum. Each atrium and ventricle are equipped with a valve to ensure the blood has unidirectional flow through the heart and consequently through the body. Bicuspid valve is located at the top right side and the mitral valve located at the top left side. While the other two valves are the pulmonary valve and the aortic valve where are located at the down right side and down left side respectively.

In the course of a day, the heart contracts and expands on average 100,000 times, pumping approximately 2,000 gallons of blood to the entire body. By opening and closing in a synchronized manner, the four valves keep the blood flowing in a forward direction. The mitral and aortic valves are the common valves are the most common

sites of heart valve disease, because of their location on the left side of the heart. The left chamber has a greater workload than right chamber because it needs to pump the blood to the entire body, whereas the right chambers only push blood into the lungs. Nowadays, severe dysfunction of heart valve now is increasingly replaced by prosthetic devices which are either mechanical valve or biological valve. However, thromboembolism and tissue regeneration are detrimental to the prosthetic device's functionality. Prosthetic valve which has complex geometry, motion, deformation, flows and the interactions with the wall and blood cause the simulation become challenging. The effort of seeking and making the perfect synthetic prosthesis have not been successful yet since there is no prosthesis can reliable for long-term life.

In most of the previous research study for human heart valve, there is usually same shape of the valve orifice was used in the analysis when the mitral valve was opened fully such as in Nakamura et al. (2006). Besides, from the past until now, some of Finite Element (FE) models of mitral valve have been developed without deeply focusing on the effect of fluid through the valve and ignore the effect of the left ventricle of the heart in the blood flow (Espino et al., 2006; Einstein et al., 2005; Loon et al., 2006). Furthermore, most of the research only analysed the valve with a single leaflet model in a tube (Loon et al., 2006; Amanifard et al., 2001) and until recently only got few more researches focused on the FSI model of mitral valve with two leaflets condition (Einstein et al., 2005; Espino et al., 2006 and Hisham et al., 2011).

1.3 PROBLEM STATEMENT

This project is limited to 2-Dimensional mitral valve and aortic valve model for cardiovascular dynamics with different size and shape depends on the different human body. The main focus is investigating the velocity performance of blood flow and the maximum displacement changes of the valve leaflet by manipulating the critical size and shapes of the leaflet. For 2-Dimensional mitral valve and aortic valve model, the investigation is on the correlation between the different shape of mitral valve and aortic valve with the blood flow through the left chamber. Since the shape of the mitral valves and the aortic valve is different, the effect of blood flow through these two valves will be changed and different. The change in blood flow may cause the heart need more

workload to pump the blood and affect the pressure applied on the muscle wall in the heart.

In this investigation, five different shapes of the mitral valve and the aortic valve were selected to study and will simulate by using the ADINA-FSI. The behaviour of the leaflets of the mitral valve and aortic valve by different shape will be focused during the investigation. The result of blood flow velocity and valve leaflet displacement changes obtained are important for use to support the future design of the prosthetic valves.

1.4 OBJECTIVES

The main objective of this project is to investigate the displacement changes on the valve leaflet based on different shape of mitral valve leaflet and aortic valve leaflet. Besides, the effect of the blood velocity when flows through different shape of the mitral valve leaflet and aortic valve leaflet were also determined.

1.5 SCOPE

The scopes of this project are as follows:

i) Mitral model and aortic model is limited to 2-dimensional (2D)
ii) Blood assumes as Newtonian and incompressible fluid
iii) Correlation is determined using numerical modelling
iv) The flow of blood is assumed in a steady state condition

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODCUTION

In this chapter, the basic knowledge which related to the human heart valve will be described in it. A simple explanation and intro to the mitral valve and aortic have been presented. Besides, the common mitral valve disease and also for aortic valve will be defined. The treatments for the heart valve disease such as repair and replacement also will be introduced. Moreover, fluid flow theory and the fundamental engineering theories also will be described which is related to the blood flow and leaflets deformation during simulation in this study. The simulation could be explained by using certain of the formulae and equations such as governing equation. Lastly, some journals regarding to simulation study which are highly related to this study will be summarized. The idea and dimension used to applying in designing the valve leaflet have been referred back to the previous study.

2.2 MITRAL VALVE

Mitral valve is a bicuspid valve Mitral valve is located between the left atrium and left ventricle, is one of the four valves in the heart that control the blow flow through into the heart. It also used to prevent the blood flowing backwards from the left ventricle into the left atrium. Mitral valve consists of several components which included annulus, chordae tendineae, papillary muscles and two leaflets which is anterior and posterior. When one or both mitral valve leaflets are dysfunctional, the mitral valve is unable to seal tightly and could cause the mitral stenosis and regurgitation occurred (Nakamura et al., 2006).

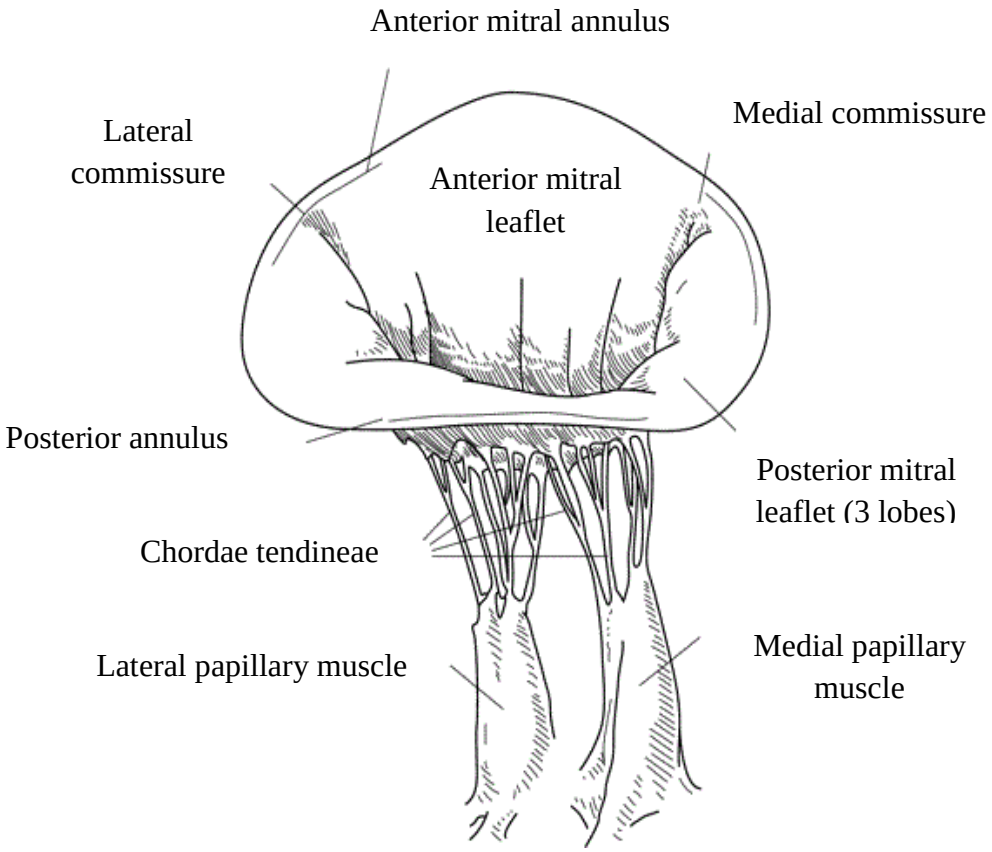


Figure 2.1: Mitral valve

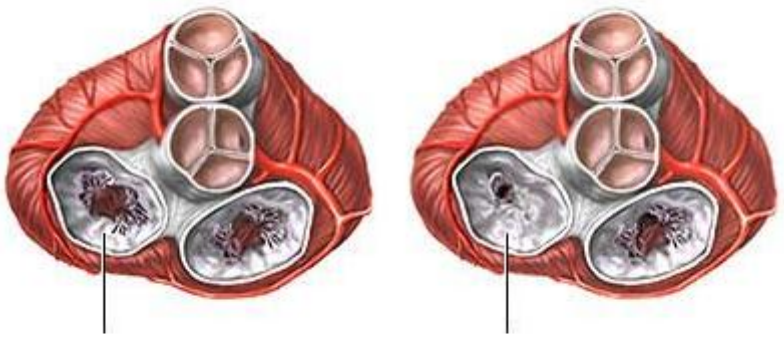
Source: Otto (2003)

2.3 MITRAL VALVE DISEASES

2.3.1 Mitral Valve Stenosis

Mitral valve stenosis is the medical term and can be explained by narrow opening of the valve and prevent the valve to open properly, which will cause the blocking of the free flow of blood. Since the mitral valve is located between the left atrium and left ventricle, the narrowing opening of the valve will result an increase pressure in the left atrium. This pressure will be transmitted back to the lungs and causing the congestion of air passage-ways. In the past, mitral stenosis was usually

caused by rheumatic fever, but fortunately for now, antibiotics treatment can prevent the rheumatic fever and its effect on the heart muscle and valves. The case of congenital mitral stenosis is rare. Mitral stenosis may cause by other reasons which are infective endocarditis, congenital anomalies and others causes like coronary artery disease or a heart attack. By narrowing the mitral valve opening, it will reduce the amount of blood that supposed to be supply forward to the body. It also will affect the atrium to be enlarged due to the high pressure build up in it and blood may backflow into lung resulted the lung disease (Otto Harvard Health Publications, 2012).



Normal mitral valve

Narrowing of mitral valve
(mitral valve stenosis)

Figure 2.2: Comparison between normal and stenosis mitral valve

Source: Harvard Health Publications (2012)

2.3.2 Mitral Valve Regurgitation

Mitral valve regurgitation means the mitral valve does not close well and cause the blood back flow into the left atrium. This back flow of blood will cause the left atrium to dilate or enlarge. However, the heart is able to compensate for the valve effect and cause mitral regurgitation is difficult to detect by without present symptoms for many years. In some rare case, mitral regurgitation may be present without symptoms for many years by affected of mitral stenosis.

Mitral regurgitation is most often caused by rheumatic heart disease, which is the heart valve damage occurring when after an acute rheumatic fever. It will cause the degeneration of the valve and the muscle that control the valve to be dysfunctional. Besides, mitral valve prolapsed and heart attack is also the usual common cause. A heart attack may disrupt a portion of the heart that used to support the position of valve and result mitral insufficiency. In severity, mitral valve regurgitation can be treated through medication. If the medication did not helpful in treatment, the two open heart surgical options which are mitral valve repair or mitral valve replacement will be considered (University Virginia Health System, 2012).

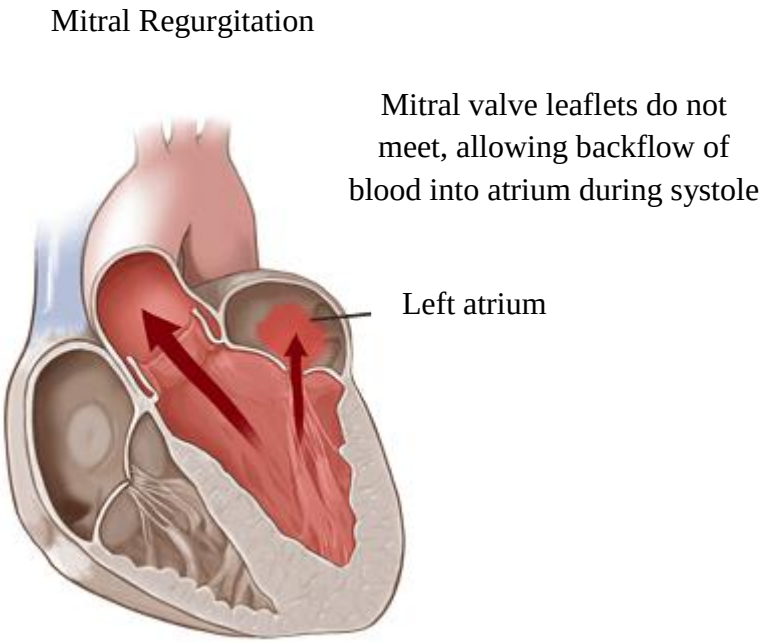


Figure 2.3: Mitral valve regurgitation

Source: University Virginia Health System (2012)

2.3.3 Mitral Valve Prolapsed

This is a common defect for heart disease and it is about 5% of the entire population has mitral prolapsed. In mitral prolapsed, the leaflet is prolapsed or may be out of its normal position to cause the valves cannot close tightly during the left atrium is emptied and left ventricle is full. It causes the blood can leak back to the left atrium and cause mitral regurgitation. In general, if there are no symptoms or the symptoms are mild, there is no treatment required (Yale School of Medicine, 2011).

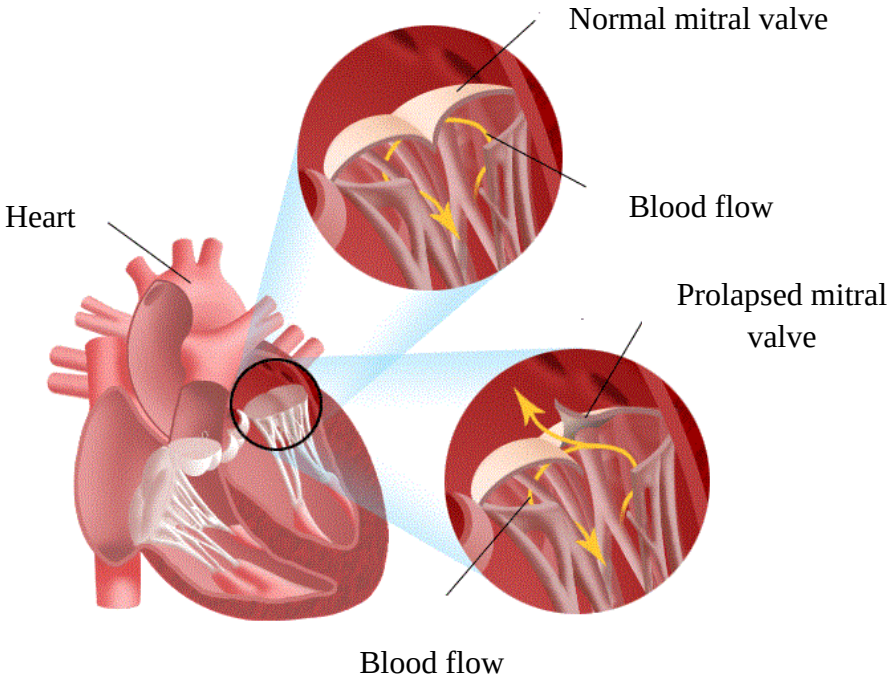


Figure 2.4: Mitral valve prolapsed

Source: Yale School of Medicine (2011)

2.4 AORTIC VALVE

Aortic valve is one of the four valves that control the blood flow form left ventricle into the aorta and pumped out to the body. Aortic valve consists of 3 half-moon-shaped pocket–like flaps of delicate tissue, as cups. Normally, these cups are perfectly aligned when the aortic valve is closed. During systole, the muscle of the left ventricle pumps the blood and the aortic valve open widely to let the blood flow freely. While during diastole, the aortic valve closes completely to prevent the blood back flow from aorta (UCLA Department of Surgery, 2004).

Figure 2.5: Aortic valve

Source: UCLA Department of Surgery (2004)

2.5 AORTIC VALVE DISEASES

2.5.1 Aortic Valve Stenosis

Aortic stenosis is a disease that same as mitral stenosis where the narrowing or obstruction in the aortic valve. The opening of aortic valves plays an important role to allow the pink oxygen-rich blood flow into aorta and get pumped out to the body. The narrowing of aortic valves will result the heart muscle must work harder to pump the blood into aorta. In most common cases, the aortic stenosis caused by aortic valve that

has three leaflets or flaps has only two leaflets open instead of three leaflets during the heart pumps. In sometimes, the aortic stenosis also may cause by the aortic valve leaflets are fused together so the valve cannot open all the way or the entire aortic valve is congenital smaller than it should be (Healthwise Incorporated, 2009).

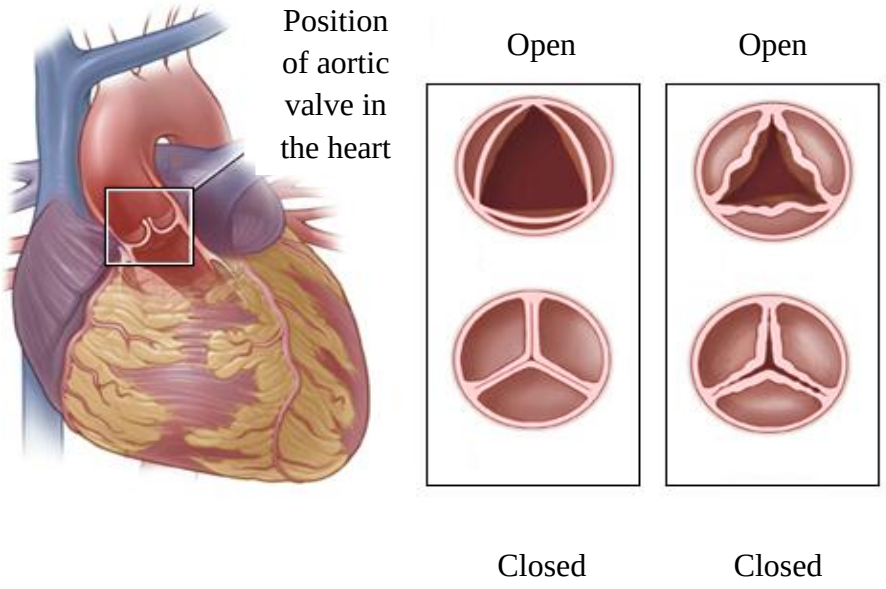


Figure 2.6: Comparison between normal and stenosis aortic valve

Source: Healthwise Incorporated (2009)

2.5.2 Aortic Valve Regurgitation

In the common case, the chronic form, aortic valve regurgitation is the consequence of the widening of the aorta region where it connects to the valve. The widening of the aorta ring will prevent the aortic valve from properly closing of the left ventricle. Besides, aortic regurgitation also may occur as the result of valve disease and rheumatic fever. Aortic valve regurgitation is same like others valve abnormalities where could produces no symptoms for many years. The symptoms like breathlessness accompanied chest pain and ankle swelling may be noticed after for many years if the condition is severe. In severe case, valve replacement may become necessary once the heart failure to operate in well (Pick, 2006).

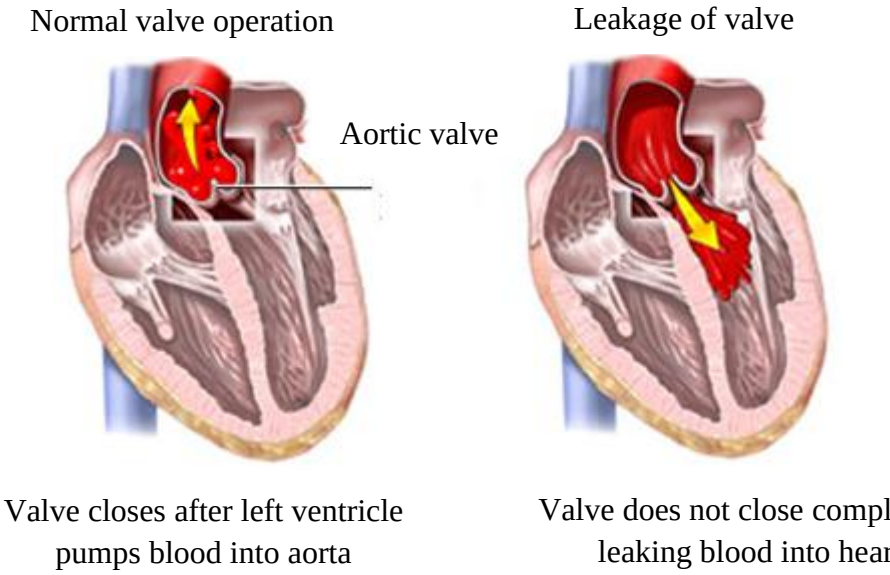


Figure 2.7: Comparison between normal and regurgitation aortic valve

Source: Pick (2006)

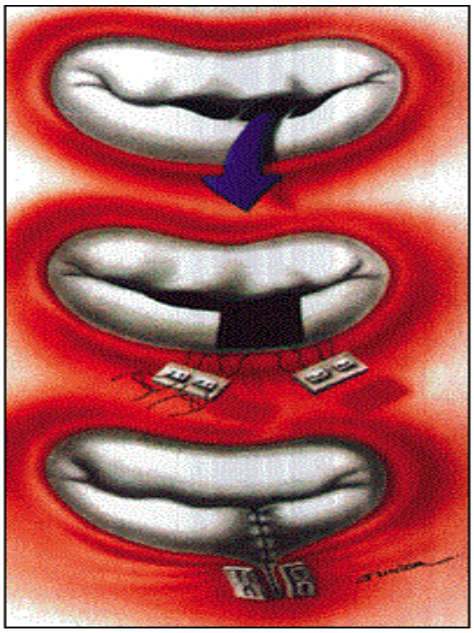
2.6 VALVE REPAIRING AND REPLACEMENT

2.6.1 Mitral Valve Repair and Replacement

This operation is performed to treat the most severe cases of mitral valve like mitral prolapsed, mitral stenosis; mitral regurgitation and others valve disease. During this operation, the mitral valve is repaired or replaced through a chest incision. In the usual case, a minimally invasive approach that involves a small incision under the right breast is selected rather than traditional incision down the front of the chest that divides the entire breast bone. By this, the patient could associate will less postoperative pain with allow to heal in a short time and reduces the period of staying in hospital.

The decision either repairing or replacing the valve is depending on the type of damage to the mitral valve. Mitral valve repair will be chosen whenever for possible rather than valve replacement for mostly all patients with leaking of mitral and narrowed mitral valve. Repairing is more successful if there is limited damage to certain areas while replacement usually preferred for people who have widespread damage or

hard, calcified mitral ring on the valve. Mitral valve repair involves removing the diseased portion of leaflets, reconstruction of the chords that control the leaflets and placement of the band or a ring to support the valve framework. Compared to valve replacement, mitral repair provides more advantages like better long-term survival, better preservation of heart function, lower risk of complication and eliminated the need for long term use of anticoagulants (Pomerantzeff et al., 1999).



Quadrangular resection of the posterior leaflet

Figure 2.8: Quadrangular resection of the posterior leaflet in patients with myxomatous degeneration

Source: Pomerantzeff et al. (1999)

Heart valve replacement involves the removal of the severely damaged valve. If a valve replacement is required, the prosthetic valve like mechanical heart valve or biological valve is used for the operation. Mechanical heart valve is constructed of metal, polymers and other material while biological valve consists of donated human or animal tissue. The damaged valve is removed by surgery and the new prosthetic valve is sewn into place. The development of blood clots in the heart may happen to those